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DESALINATION OF AGRICULTURAL TILE DRAINAGE

Bryan R. Sword

Robert S. Kerr Water Research Center
Ada, Oklahoma

May 1971

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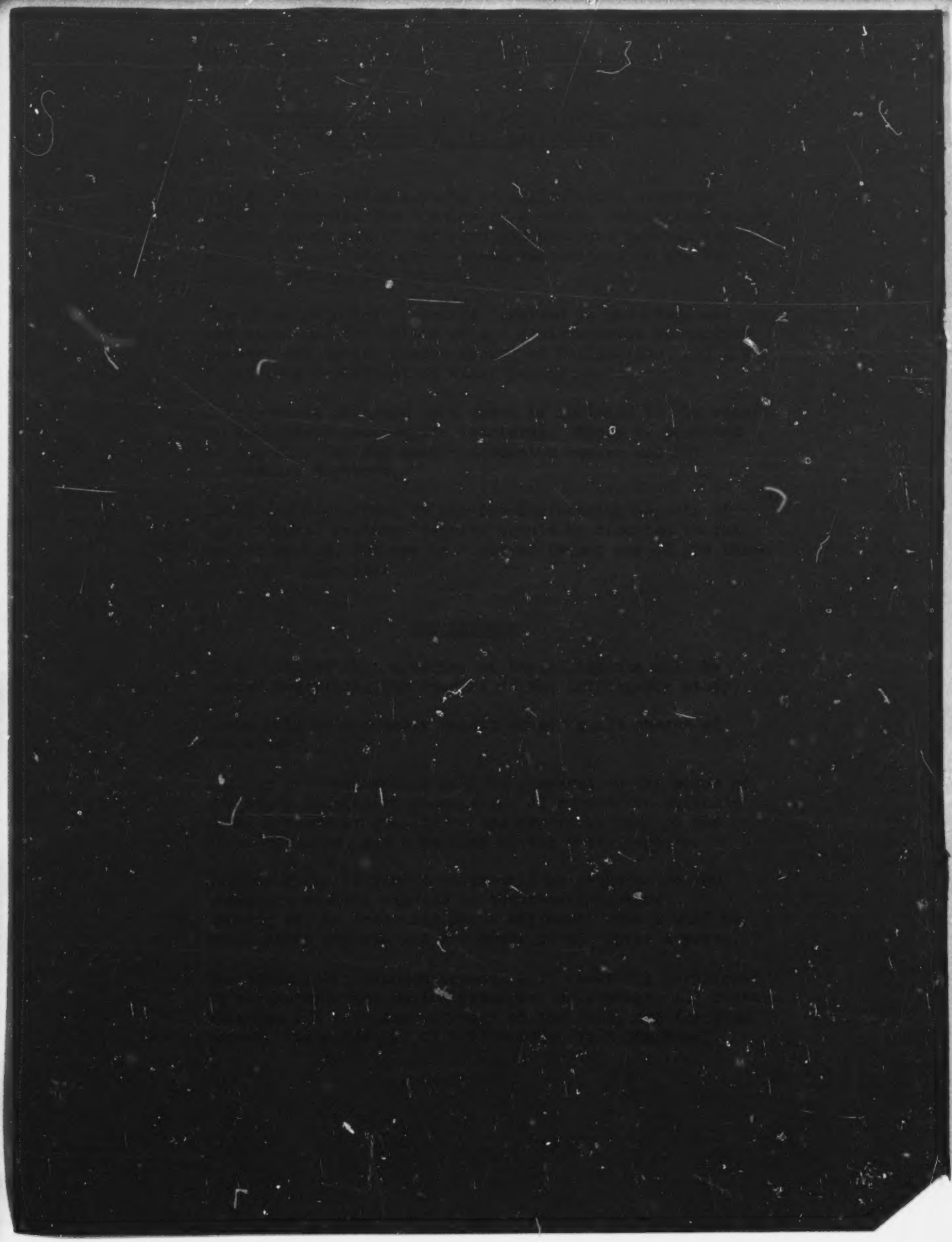

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~~This report was submitted in partial fulfillment of Project No. 13030 ELY under sponsorship of the Environmental Protection Agency.~~

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BIO-ENGINEERING ASPECTS OF AGRICULTURAL DRAINAGE
SAN JOAQUIN VALLEY, CALIFORNIA

DESALINATION
OF
AGRICULTURAL TILE DRAINAGE

Study Conducted by

Robert S. Kerr Water Research Center
Treatment and Control Research Program
Ada, Oklahoma

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PROGRAM #13030 ELY
May 1971

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This report has been reviewed by the Water Quality Office of the Environmental Protection Agency, U. S. Bureau of Reclamation, and the California Department of Water Resources and has been approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the reviewing agencies nor does mention of trade names or commercial products constitute endorsement or recommendation for use by either of the reviewing agencies.

ABSTRACT

Investigations were made to determine the technical feasibility of desalination of tile drainage. The source of the tile drainage was a 400-acre field near Firebaugh, California. Reverse Osmosis (RO) and Electrodialysis (ED) processes were studied. Two RO membrane stacks were investigated. The first, a high salt rejection, low product yield, was operated on variable quality (3000-7000 mg/l TDS) irrigation return water. In the 7-month investigation period TDS removal efficiencies decreased from 93 percent to 80 percent salt rejection and the product flux decreased from 12 gal/ft^2/day to less than 9 gal/ft^2/day. The 20 mg/l of nitrate-nitrogen and 8 mg/l of boron contained in the influent were not effectively rejected. The second RO stack and the ED unit were operated on return waters that were controlled to have a 3000 mg/l TDS. The second RO stack was designed for a high product rate and low salt rejection. The TDS removal remained at 85 percent for a 3-month run. Product flux decreased from over 19 gal/ft^2/day to less than 12 gal/ft^2/day. Nitrate and boron rejection was low. The ED data are based on a single pass through the membrane stack. The TDS removal varied from 35 percent to 15 percent. The nitrate removal rate was greater than the TDS removal. Boron removal was negligible. It is estimated that the costs for the two processes are approximately equal--$320 per million gallons of product.

This report was submitted in partial fulfillment of Project No. 13030 ELY under sponsorship of the Environmental Protection Agency.

BACKGROUND

This report is one of a series which presents the findings of intensive interagency investigations of practical means to control the nitrate concentration in subsurface agricultural wastewater prior to its discharge into other water. The primary participants in the program are the Environmental Protection Agency, the United States Bureau of Reclamation, and the California Department of Water Resources, but several other agencies also are cooperating in the program. These three agencies initiated the program because they are responsible for providing a system for disposing of subsurface agricultural wastewater from the San Joaquin Valley of California and protecting water quality in California's water bodies. Other agencies cooperated in the program by providing particular knowledge pertaining to specific parts of the overall task.

The ultimate need to provide subsurface drainage for large areas of agricultural land in the western and southern San Joaquin Valley has been recognized for some time. In 1954, the Bureau of Reclamation included a drain in its feasibility report of the San Luis Unit. In 1957, the California Department of Water Resources initiated an investigation to assess the extent of salinity and high ground-water problems and to develop plans for drainage and export facilities. The Burns-Porter Act, in 1960, authorized San Joaquin Valley drainage facilities as a part of the California Water Plan.

The authorizing legislation for the San Luis Unit of the Bureau of Reclamation's Central Valley Project, Public Law 86-488, passed in June 1960, included drainage facilities to serve project lands. This Act required that the Secretary of Interior either provide for constructing the San Luis Drain to the Delta or receive satisfactory assurance that the State of California would provide a master drain for the San Joaquin Valley that would adequately serve the San Luis Unit.

Investigations by the Bureau of Reclamation and the Department of Water Resources revealed that serious drainage problems already exist and that areas requiring subsurface drainage would probably exceed 1,000,000 acres by the year 2020. Disposal of the drainage into the Sacramento-San Joaquin Delta near Antioch, California, was found to be the least costly alternative plan.

Preliminary data indicated the drainage water would be relatively high in nitrogen. The Environmental Protection Agency conducted a study to determine the effect of discharging such drainage water on the quality of water in the San Francisco Bay and Delta. Upon completion of this study in 1967, the Agency's report concluded that the nitrogen content of untreated drainage waters could have significant adverse effects upon the fish and recreation values of the receiving waters. The report recommended a three-year research program to establish the economic feasibility of nitrate-nitrogen removal.

As a consequence, the three agencies formed the Interagency Agricultural Wastewater Study Group and developed a three-year cooperative research program which assigned specific areas of responsibility to each of the nitrogen conditions in the potential drainage areas, possible control of nitrates at the source, prediction of drainage quality, changes in nitrogen in transit, and methods of nitrogen removal from drain waters including biological-chemical processes and desalination.

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SECTION I

SUMMARY AND CONCLUSIONS

Two reverse osmosis (RO) membrane stacks and an electrodialysis (ED) unit were operated on agricultural tile drainage waters.

The initial RO stack received an influent with varying total dissolved solids (TDS) content which ranged from approximately 3000 mg/l to 7000 mg/l. When operated at peak performance, this set of membranes was able to remove over 90 percent of the influent TDS; however, nitrate and boron removal averaged less than 27 percent. The product recovery for this stack averaged approximately 37 percent. The second RO stack used was able to achieve 85 percent removal of a constant 3000 mg/l TDS influent, but nitrate and boron removal was negligible. Although low nitrate rejection was characteristic of the reverse osmosis membranes used for these experiments, it is believed that reverse osmosis units using current technology, especially new membranes, could be expected to achieve a higher nitrate rejection than reported herein. The product recovery for this stack averaged approximately 40 percent; however, this lower-than-expected recovery was caused by internal damage to the reverse osmosis stack.

The electrodialysis unit had an average TDS removal of 23 percent, with a maximum removal of 36 percent, when supplied with a 3000 mg/l TDS influent, based on a single pass through the membrane stack. Although the ED unit did not remove boron at any time, nitrate was removed at a rate averaging 1.98 times that calculated for TDS removal. Product recovery based on a single pass remained constant at 75 percent. Economic data taken from literature indicate that water produced by both RO and ED costs approximately $0.32 per thousand gallons.

It was concluded from the experimental data that desalination of San Joaquin Valley subsurface agricultural return flow is technically feasible. However, it does not appear at the present time that direct reuse of the water as an irrigation source is economically possible.

SECTION II

INTRODUCTION

In October 1966, the Office of Saline Water and the Federal Water Quality Administration (now the Environmental Protection Agency) began cooperative research into the use of desalination processes to remove salt from subsurface agricultural wastewaters (tile drainage). This program was conducted from June 1967 to September 1968 in conjunction with the cooperative nitrogen removal studies being performed at the Interagency Agricultural Wastewater Treatment Center (IAWTC) near Firebaugh, California. The primary objective was to determine the technical feasibility of desalinating the drainage waters. Secondary objectives were to produce desalting cost estimates and to provide performance data on the removal of nitrate and boron from the wastewaters.

The information provided by these experiments can be used to consider reuse of the water for agriculture and to compare reclamation costs and costs of future imports of water into the San Joaquin Valley. Of particular interest when considering reuse is the removal of boron. Tile drainage in the western portion of the San Joaquin Valley typically has relatively high concentrations of this element. The removal of nitrogen from the wastewater was also studied.

Theory of Process Operations

Reverse osmosis and electrodialysis were the two desalination processes applied in this study. Both processes accomplished essentially the same result; however, theories of their operation differ. A discussion of their characteristics follows.

Reverse Osmosis

When two solutions of differing concentrations (but with a common solvent) are separated by a semipermeable membrane[1/], solvent will flow from the weaker solution to the more concentrated solution. The process is known as osmosis and is illustrated in Figure 1. Osmotic pressure (p) is a measure of the difference between the diffusion pressure of solvent (water) molecules in the two solutions. Solvent tends to flow from an area of high diffusion pressure to an area of low diffusion pressure until equilibrium is established. If a pressure (P) greater than osmotic pressure (p) is applied to the more concentrated solution side of the membrane, solvent (water) is forced through the membrane in a direction opposite to normal osmotic flow. This is the reverse osmosis

1/ A membrane more permeable to solvent than to solute molecules is said to be differentially permeable or semipermeable.

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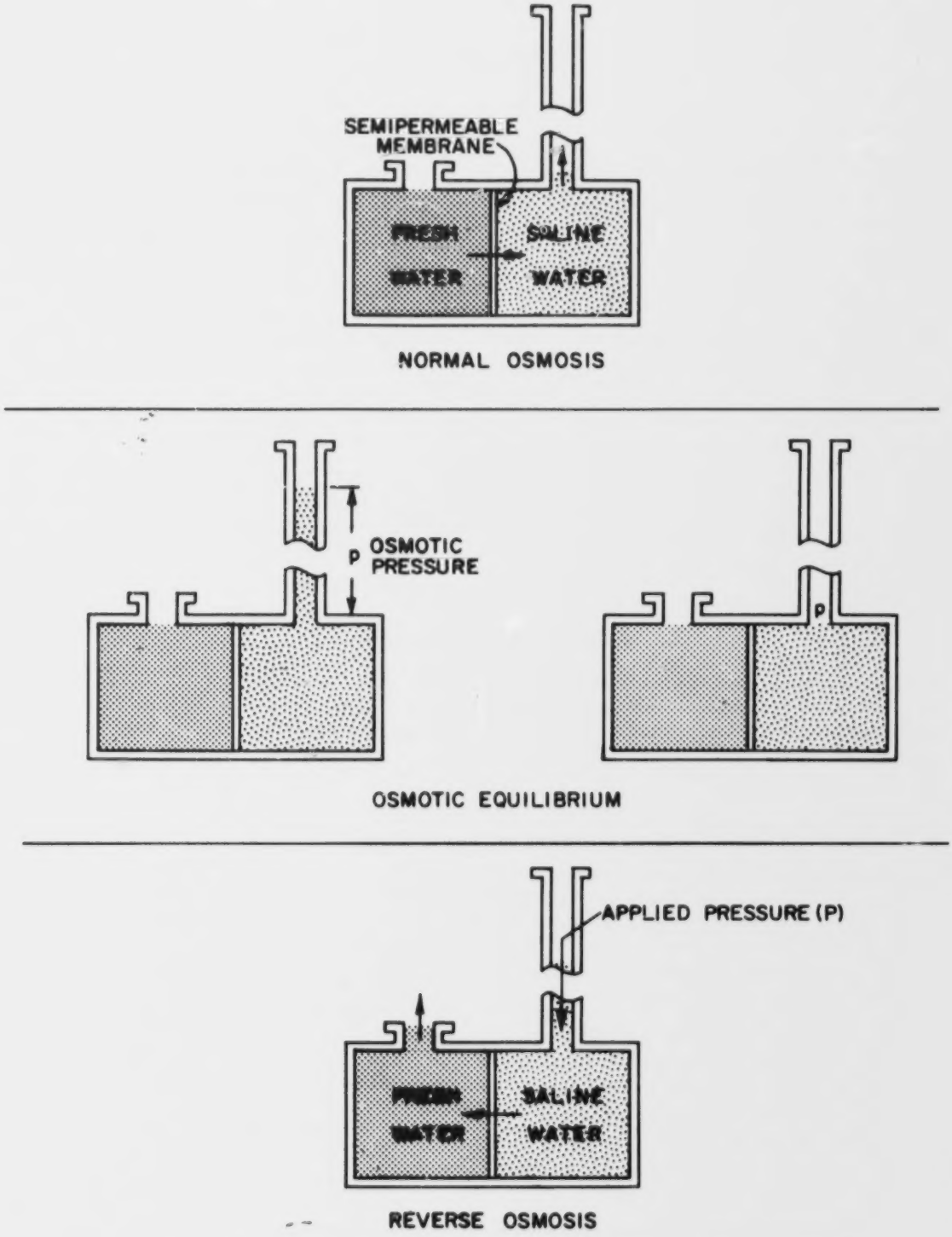

FIGURE 1 - THE PRINCIPLE OF REVERSE OSMOSIS

phenomenon used in desalination. In theory, the flow of water through the membrane is approximately proportional to the net pressure (applied pressure minus osmotic pressure), and the amount of salt passing through a less than ideal semipermeable membrane depends primarily on the gradient in salt concentration between the two solutions. In practice, however, flow limitations have been shown to result from osmotic pressure increases due to concentration build-up in the liquid boundary layer on the brine side of the membrane, thereby decreasing the net pressure, and from salt precipitation or other deposits onto the membrane surface (1). The salt precipitation is an operational problem. Depending on the composition of the brine water, precautions such as pH control and chemical additions, may be necessary to prevent the accumulation of precipitate onto the membranes.

Electrodialysis

The removal of ions from a saline solution by electrodialysis depends on the basic principle that positively and negatively charged poles attract. Therefore, if a direct current potential is applied across a solution of salt in water by means of two electrodes inserted in the solution, the cations will be attracted toward the cathode and the anions will be attracted toward the anode. This movement of ions shown in Figure 2 can be used to advantage if ion selective membranes were so placed that they isolate a purified zone from which the ions had been removed. For this purpose, cation and anion permselective membranes were developed, each membrane allowing only cations or anions to pass through respectively. Use of these membranes to form watertight compartments in a salt solution and the electrical potential will result in a demineralized central compartment. As in reverse osmosis, an over-concentration of salts in the compartments receiving the ions will lead to precipitation of salts onto and possibly in the membrane. Precautions were taken during operation to minimize such occurrences.

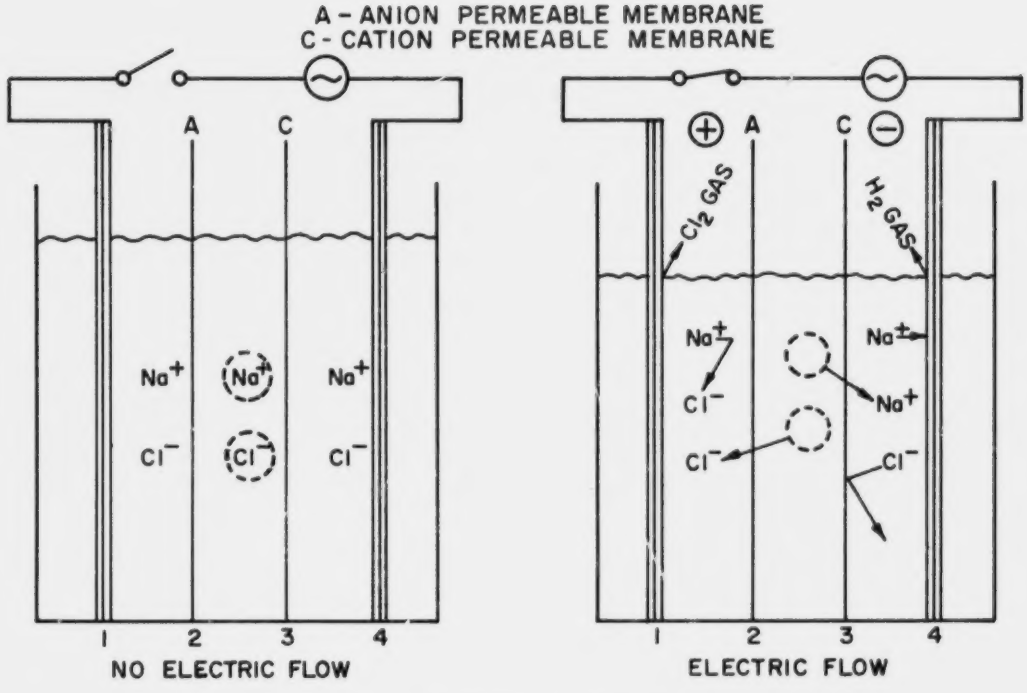

FIGURE 2 - THE PRINCIPLE OF ELECTRODIALYSIS

SECTION III

EXPERIMENTAL EQUIPMENT AND PROCEDURES

The two units used to demonstrate these processes were an Aerojet-General Reverse Osmosis Water Purifier (Model 1-560B-1) and an Ionics Electrodialysis Demineralizer (Model 300-B-3). The features of these units, the quality of the irrigation return waters, and the methods of evaluating the processes are described in this section.

Reverse Osmosis Unit

The main components of the unit were a pressure vessel, a control console, a high-pressure positive displacement pump, and two banks of nine 5-micron cartridge filters (Figures 3 and 4). Within the pressure vessel were 600 square feet of semipermeable cellulose acetate membranes. The membrane and support plate combinations were divided into five modules, which composed the reverse osmosis membrane stack. The membrane and support plate were fabricated to separate the feed water into a product stream and a brine or waste stream (Figure 5). The control console consisted of an instrumentation panel, a pump control panel, and an externally mounted pressure switch. The instrumentation panel included the following: pump suction line pressure indicator, pump discharge line pressure indicator, feed water temperature indicator, product water conductivity indicator, and a differential pressure indicator to monitor the difference between the pressure vessel inlet and outlet pressure. Flows were monitored by flow meters installed on the effluent lines of the product and brine streams. The maximum feed flow possible by means of the positive displacement pump was 13 gpm. However, this flow was varied, depending on the recovery desired. Percent recovery was increased by reducing the quantity of influent and maintaining a constant quantity of product effluent.

Because of the ionic makeup of the tile drainage, there existed a distinct possibility that either calcium carbonate or calcium sulfate, would precipitate onto the membranes. To prevent this, the tile drainage was pretreated by controlling the pH to prevent calcium carbonate scaling and by adding a chemical to inhibit precipitation of calcium sulfate. The pH of the influent irrigation return waters was lowered from approximately 7.4 to a range of 5.5 to 5.8 by the injection of concentrated sulfuric acid. The chemical inhibitor was Cynamer P-35 1/, which was injected at an average rate of 3 mg/l. Both chemicals were added by positive displacement pumps.

Two membrane stacks were tested at the Center. The first was manufactured to have a "tight" membrane. This stack (Stack I) was operated at 750 pounds per square inch gage pressure (psig). Its main characteristics

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1/ Manufactured by the American Cynamid Company

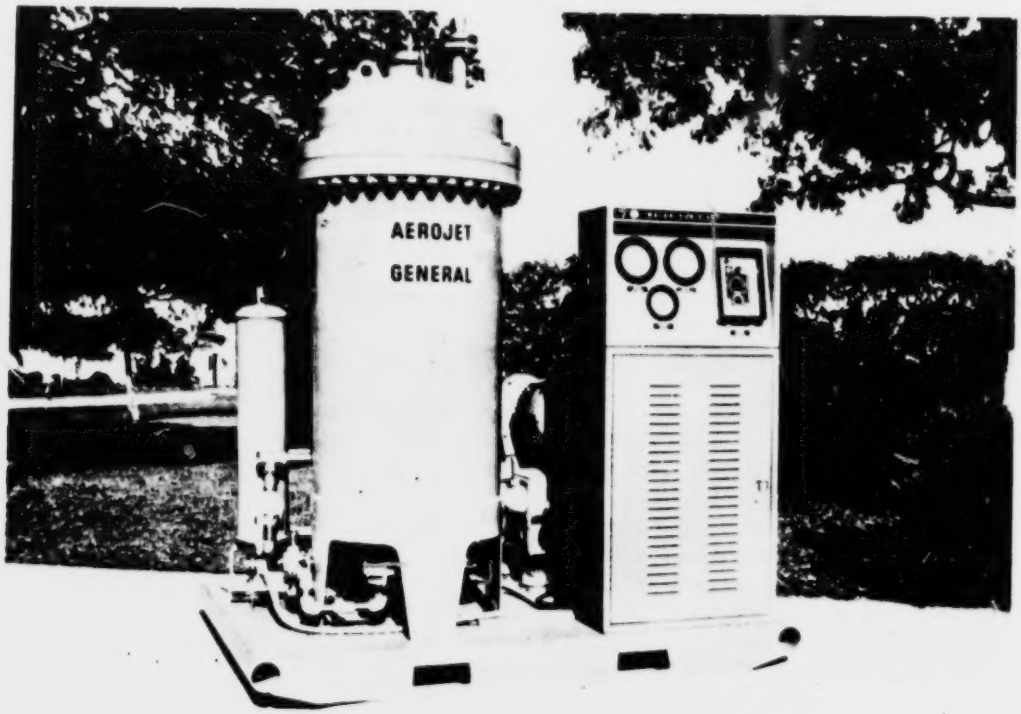

FIGURE 3 - AEROJET GENERAL REVERSE OSMOSIS WATER PURIFIER
MODEL 1-560B-1

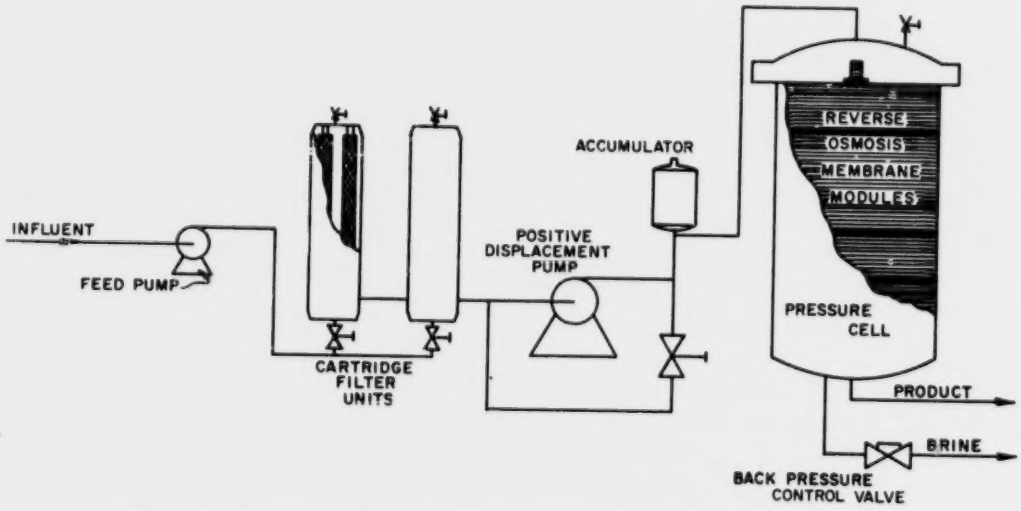

FIGURE 4 - AEROJET GENERAL REVERSE OSMOSIS UNIT - MODEL 1-560-B-1
FLOW SCHEMATIC

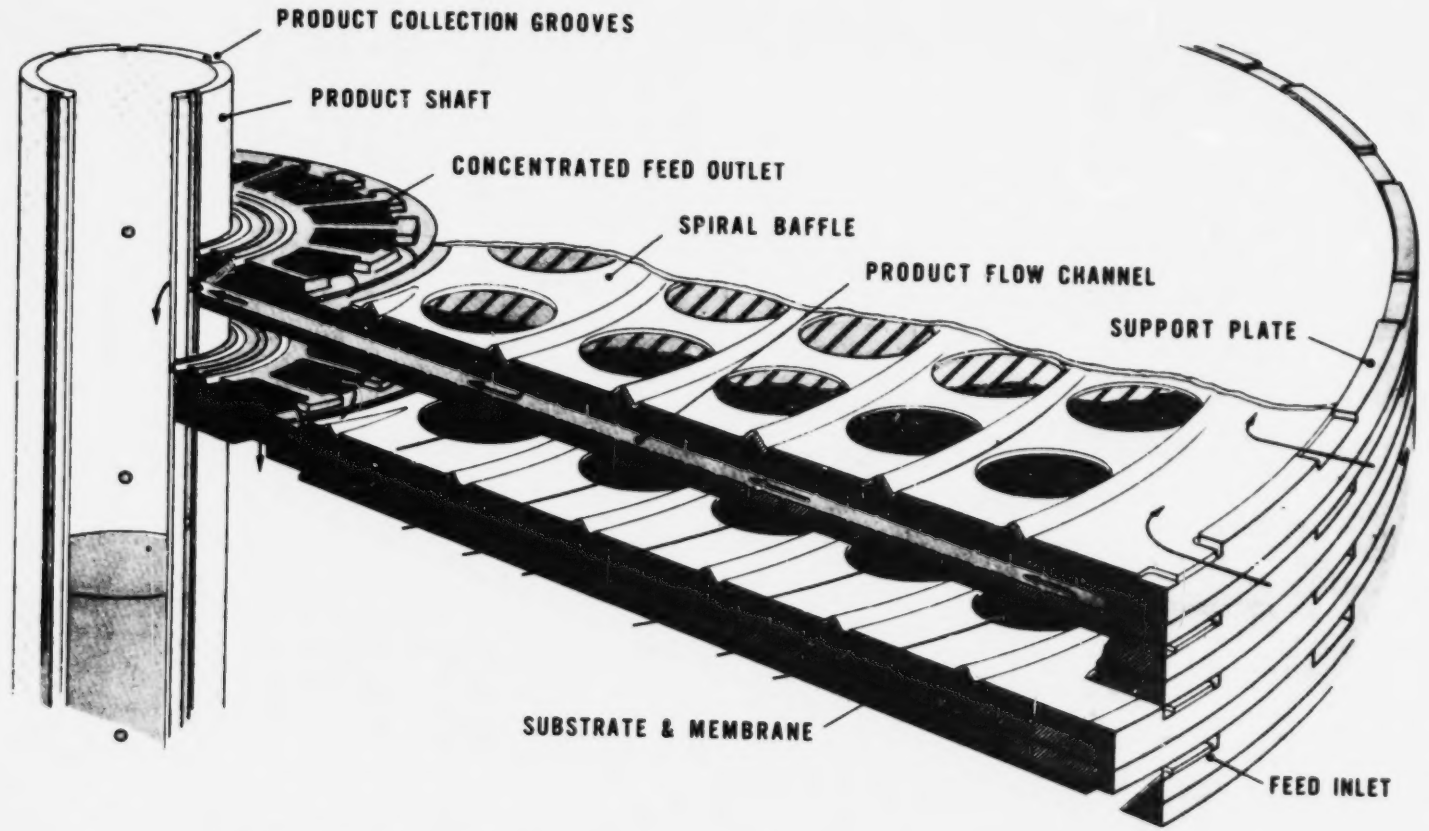

FIGURE 5 - WATER FLOW THROUGH CIRCULAR DESALINATION PLATE

were a low flux and high salt rejection capacity. The second (Stack II) was designed to have a "loose" membrane. It was operated at an applied pressure of 350 psig. The membrane was characterized by a relatively high flux and a low salt rejection ability.

Electrodialysis Unit

The main feature of the Ionics' Electrodialysis (ED) unit was the electrical membrane stack (Figure 6) which consisted of 150 membrane-spacer combinations. Each combination consisted of an anion and cation membrane separated by water flow guides. The water flow guides separate the water flow through the stack into two main streams, the dilute (product) and brine streams. A pressure differential of approximately 1 psig was maintained between the two streams. The brine stream was confined under the lower pressure. Thus, if a membrane became damaged water could only flow from the dilute to the brine, thereby removing the possibility that the dilute stream could become contaminated.

Other features of the unit were a control panel to monitor pump pressures, stack pressure differential, and product conductivity, and a rectifier that included a voltmeter and an ammeter to monitor voltage and amperage across the membrane stack. A constant electromotive force of 275 volts was maintained across the stack for all experiments; the amperage varied, depending on feed salinity, water temperature, and membrane conditions.

Basically, the unit operates by separating the water flow through the unit into the two streams previously mentioned. A flow schematic showing the routing of these streams is presented in Figure 7. The dilute stream is formed by water from which the salt ions are removed as it passes through the membrane stack at the rate of 25 gpm. Ions removed from the dilute stream were collected by a recirculating brine stream. Feed water was constantly added to the brine stream so that the ion concentrations remained below their saturation limit. This addition was referred to as the brine stream blow down.

Precautions were necessary to avoid calcium carbonate and/or calcium sulfate scaling on the brine side of the membranes. Calcium carbonate scaling was prevented by injecting a 20 percent sulfuric acid solution to keep the brine stream pH in a range of 5.5 to 5.8. Calcium sulfate scaling was prevented by using a brine stream blow down rate of 6 to 8 gpm which was sufficient to prevent saturation of calcium and sulfate ions. However, had it been necessary, a chemical inhibitor similar to that used in the RO could have been injected.

Feed Water Blending System

The tile drainage that came directly from the field was used as feed water for evaluation of Stack I of the RO and preliminary testing of the ED unit.

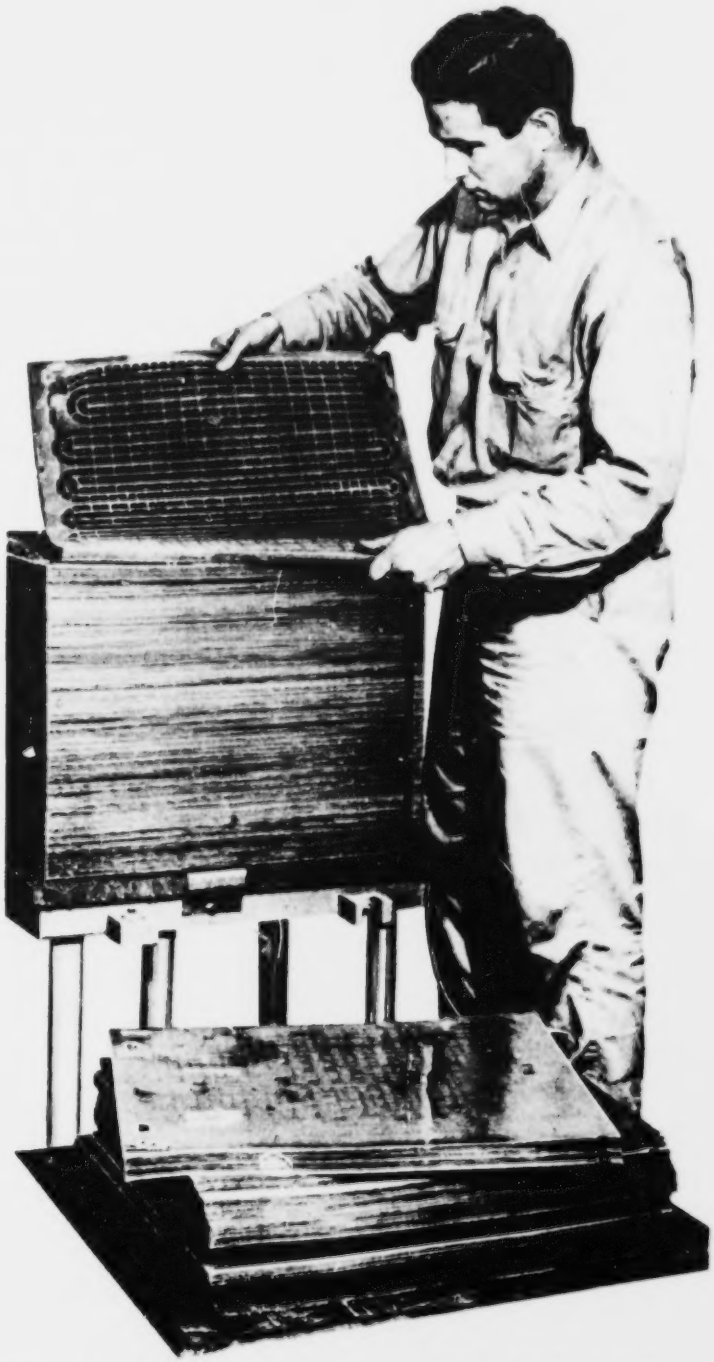

FIGURE 6 - IONICS, INC. ELECTRODIALYSIS UNIT
MODEL 300-B-3 MEMBRANE STACK

REPRODUCED WITH THE
PERMISSION OF IONICS, INC.

The salinity of these waters varied seasonally from 2500 to 7600 mg/l total dissolved solids (TDS). The variations in influent TDS made evaluations of the units difficult; therefore, a constant salinity feed was provided by installing a blending system which mixed water from a source having low TDS with the tile drainage to provide a constant salinity of 3000 mg/l TDS. A schematic of this system is shown in Figure 8. Suspended solids were removed from the low salinity water before it was mixed with the tile drainage by the use of a pressure sand filter and a diatomaceous earth filter. In actual practice, the sand filter was usually bypassed because it caused pressure fluctuations that affected the performance of the diatomaceous earth filter. Varying flow rates of blended water were used, depending on the TDS concentration of the tile drainage.

Influent Water Quality

The water used for the experimental work was taken from a tile drainage system that serviced a 400-acre field. The land was used primarily to cultivate rice during the summer and to grow barley during the winter. The amount of irrigation water needed by these two crops differs greatly. This difference causes a seasonal change in tile flow and in concentration of the dissolved minerals. The lower concentrations occur in the summer. The mineral concentration ranges of the tile drainage used at the Interagency Agricultural Wastewater Treatment Center are listed in Table 1.

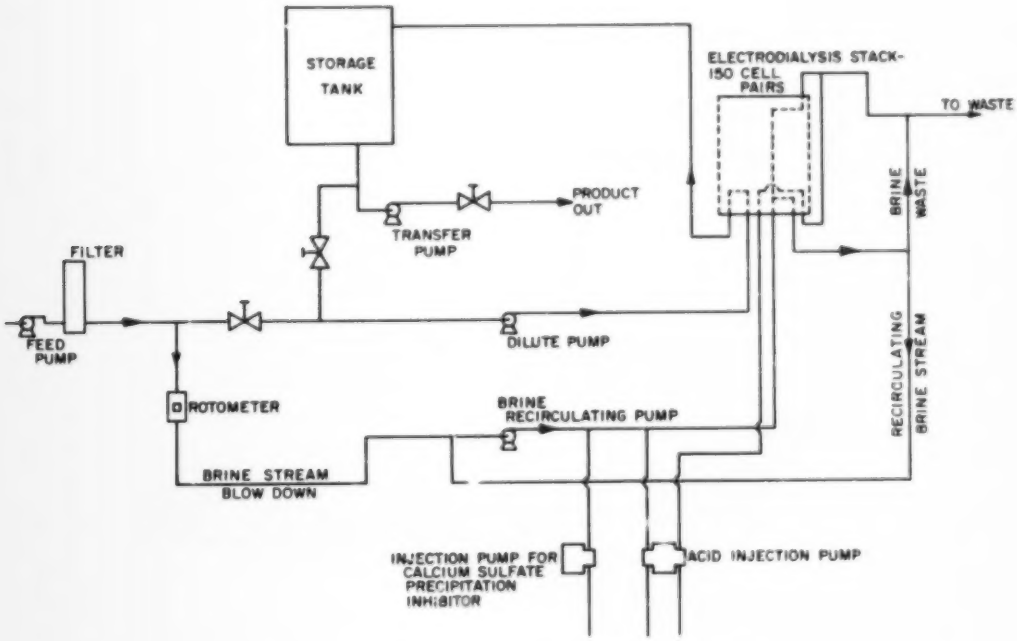

FIGURE 7 - IONICS ELECTRODIALYSIS FLOW SCHEMATIC

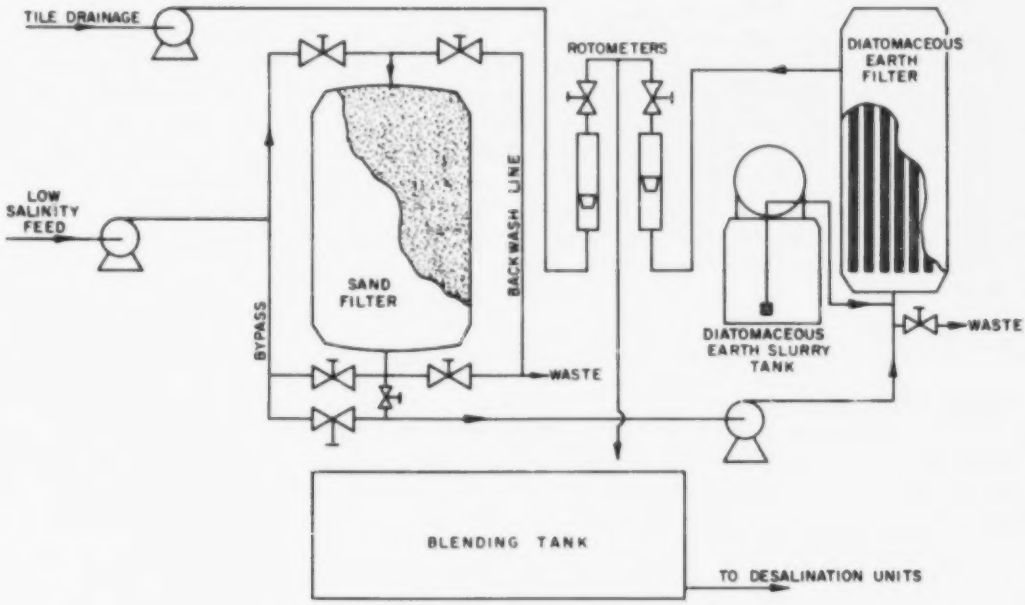

FIGURE 8 - SCHEMATIC OF BLENDING SYSTEM

TABLE 1
CHARACTERISTICS OF TILE DRAINAGE USED AT THE IAWTC
AND AVERAGE MINERAL CONCENTRATIONS OF IRRIGATION WATERS

CONSTITUENT	RANGE OF MINERAL CONCENTRATIONS IN TILE DRAINAGE mg/l	AVERAGE MINERAL CONCENTRATION OF IRRIGATION WATER mg/l
Bicarbonate	280-330	90
Boron	4-15	0.3
Calcium	160-390	20
Chloride	310-640	60
Magnesium	70-230	10
Nitrogen	5-25	1
Phosphate	0.13-0.33	0.5
Potassium	4-11	3
Sodium	620-2050	50
Sulfate	1500-3900	65
Pesticides (CHC)	0.001	
Total Dissolved Solids	2500-7600	300
5 Day BOD	1-3	
COD	10-20	
Dissolved Oxygen	7-9	

The nitrogen in the tile drainage was essentially in the form of nitrate. Nitrite-nitrogen was not detected in concentrations greater than 0.1 mg/l; organic nitrogen was generally constant at a concentration of approximately 0.4 mg/l; and ammonia nitrogen concentrations were usually not detectable. A characteristic of this water is the high concentration of sulfate, which is the dominant anion. A high concentration of sulfate in conjunction with calcium and carbonate make the pretreatment previously described a necessity. Another characteristic of the San Joaquin Valley tile drainage is the high concentration of boron, an element which is toxic to many crops in concentrations over 1 mg/l.

Sampling and Analytical Analyses

All operational parameters (pump pressures, electrical conductivity, pH, etc.) for both units were monitored at four-hour intervals. Electrical conductivity was monitored by a Wheatstone Bridge and conductivity cell; pH was monitored with a glass electrode. A correlation between electrical conductivity and total dissolved solids was determined on a weekly basis. The following ions were determined periodically; calcium, magnesium, sodium, potassium, boron, sulfate, carbonate, chloride, nitrate, total iron, silica, and total alkalinity. All analyses were determined by the procedures described in "Standard Methods for the Examination of Water and Wastewaters" (2).

SECTION IV

RESULTS AND DISCUSSION

The overall experiments with the two desalination units were limited to unit performance, with little emphasis given to process cost or brine disposal methods.

Reverse Osmosis

The first part of this section deals with the performance of the initial RO stack and the second part describes the performance of the second RO stack that received the blended 3000 mg/l TDS water. Cost evaluation of operating the reverse osmosis unit was performed only on the second stack.

Reverse Osmosis - Stack I

This reverse osmosis stack was operated from early June 1967 to mid-January 1968. The first two months of operation were mainly devoted to familiarization and correction of operational problems. These problems, which were mostly mechanical, did not appear to greatly affect the initial performance of the unit.

TDS Removal. The unit received an influent TDS concentration that varied from less than 3000 mg/l to approximately 7000 mg/l. For the first three months the membranes produced a product containing less than 500 mg/l of TDS with an average salt rejection of more than 90 percent. The changes in influent and product TDS and also the percent of TDS removed are illustrated in Figure 9. Typical analyses of the minerals in the unit's influent, product, and brine stream are presented in Table 2.

During the unit's operation, the product salinity fluctuated with the influent salinity. Such fluctuation is normal because of increased passage of dissolved minerals through the membrane by pore transport. However, the continued decrease in product quality after October 1967 shown in Figure 9 was attributed to biological fouling and subsequent membrane deterioration. Biological degradation of the membranes may have begun when operations were suspended for extended periods of maintenance.

Variations in Membrane Flux. The flux for this stack reached its highest point, 13 gallons per square foot of membrane per day (Figure 10), on the first day of operation and then generally declined throughout the experimental period. Only in October 1967, when a higher-than-normal pressure was applied, did a significant rise in flux again occur. The flux decreased partly because a rise in influent TDS caused the osmotic pressure to increase. However, the degree to which flux dropped is probably due in part to another factor. It is known that under the

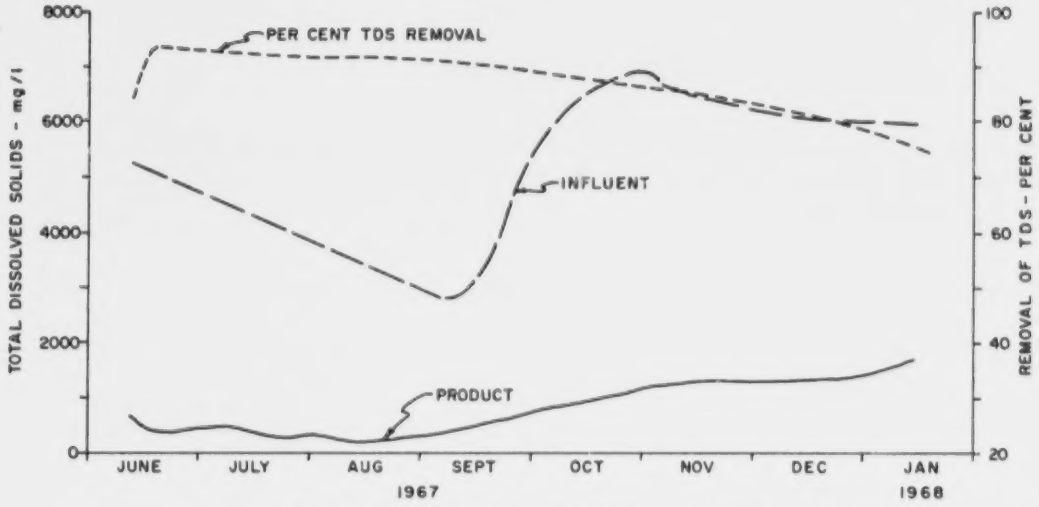

FIGURE 9 - REVERSE OSMOSIS DATA - STACK I
TOTAL DISSOLVED SOLIDS AND PER CENT REMOVAL OF TDS VERSUS TIME

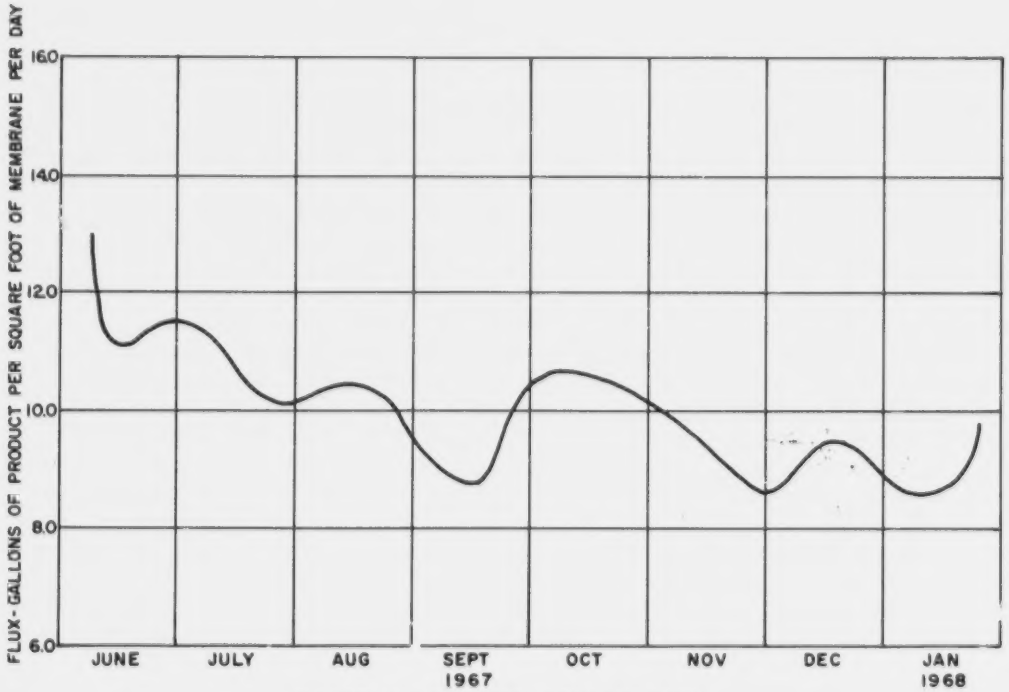

FIGURE 10 - REVERSE OSMOSIS DATA
STACK I
PRODUCT FLUX VERSUS TIME

TABLE 2

REVERSE OSMOSIS
STACK I
MINERAL ANALYSIS

Operating Conditions

Date of Sample - July 14, 1967
Operating Pressure, psig - - - - - - - - - - - - - - - - 750
pH of feed water - 5.5

Flow Rates GPM	Influent	12.5
	Product	4.2
	Brine	8.3

CONSTITUENT	CONCENTRATION - mg/l INFLUENT	PRODUCT	BRINE	PERCENT REJECTION
Calcium	230	3.3	347	99
Magnesium	111	1.7	215	98
Sodium	862	82	1350	90
Potassium	3.4	0.0	5.1	100
Boron	8.2	6.1	8.4	25
Sulfate	2360	28	3720	99
Bicarbonate	98	16	140	84
Chloride	314	94	440	70
Nitrate	34	29	37	15
Iron (total)	0.02	0.02	0.02	0
Silicon	42	13	58	69
Total Alkalinity	80	13	136	84
TDS	4230	304	6400	93
pH*	6.4	5.4	6.5	-

* pH of samples at time of analysis.

normally high operating pressures, reverse osmosis membranes do show a decreasing flux, due to what is usually called "compaction". This is most likely the main reason for the observed drop in flux.

Product Recovery. Of particular importance in any desalination experiment is the amount of brine that must ultimately be disposed of. Depending on geographical location, the cost of such disposal may equal the cost of producing the desired product water. Table 3 summarizes the product recovery achieved with this stack. The percent product recovery was controlled by varying the quantity of influent of the unit. Therefore,

TABLE 3

REVERSE OSMOSIS DATA - STACK I
PRODUCT/BRINE PRODUCTION

MONTH	PRODUCT FLOW GPM	PRODUCT RECOVERY PERCENT	BRINE/PRODUCT RATIO
June	4.1	37	1.7
July	3.9	37	1.7
August	3.8	37	1.7
September	3.4	37	1.7
October	3.8	33	2.0
November	3.4	36	1.8
December	3.3	38	1.6
January	3.2	40	1.5
Average	3.6	37	

although the amount of product generally decreased, the percent recovery was maintained by decreasing the total flow through the unit. This particular stack produced from 1.5 to 2 times as much brine as product.

Nitrate and Boron Removal. The nitrate removal of this stack varied from 0 to 49 percent, with an average of 27 percent. The boron removal ranged from 8 to 35 percent, with an average of 21 percent. Both ions were removed at substantially lower percentage than the general TDS removal.

In a separate experiment conducted by Aerojet-General with the same type of membranes, the rejection of nitrate was shown to be highly dependent on the presence or absence of the sulfate and/or chloride ion (3). In a solution containing 2000 mg/l calcium sulfate, 2000 mg/l sodium chloride, and 50 mg/l sodium nitrate, approximately 82 percent of the nitrate and approximately 98 percent of the calcium sulfate and sodium chloride were rejected. In a second solution containing 2000 mg/l calcium sulfate and 50 mg/l sodium nitrate less than 20 percent of the nitrate was rejected. In a third solution containing approximately 500 mg/l sodium chloride and 50 mg/l sodium nitrate, both nitrate and chloride were rejected at approximately a 97 percent level. These experiments demonstrated that it is possible to observe a range of nitrate permeations, depending upon the

presence of sulfate or other highly rejected anions. The results from the second solution agreed well with the results obtained from the stack operated on strictly tile drainage.

Reverse Osmosis - Stack II

The second stack of membranes used in the experiments was operated from July to September 1968 for a total of approximately 10 weeks. The operation was terminated because an error in factory assembly increased the differential pressure through the membrane stack. Inspection of the stack showed that an aluminum washer had disintegrated and blocked the brine stream flow paths. This shortened the expected life of the membranes considerably.

TDS Removal. This stack was operated with the TDS blending system previously described. It received an influent having a more constant level of TDS concentration at approximately 3000 mg/l (Figure 11). The

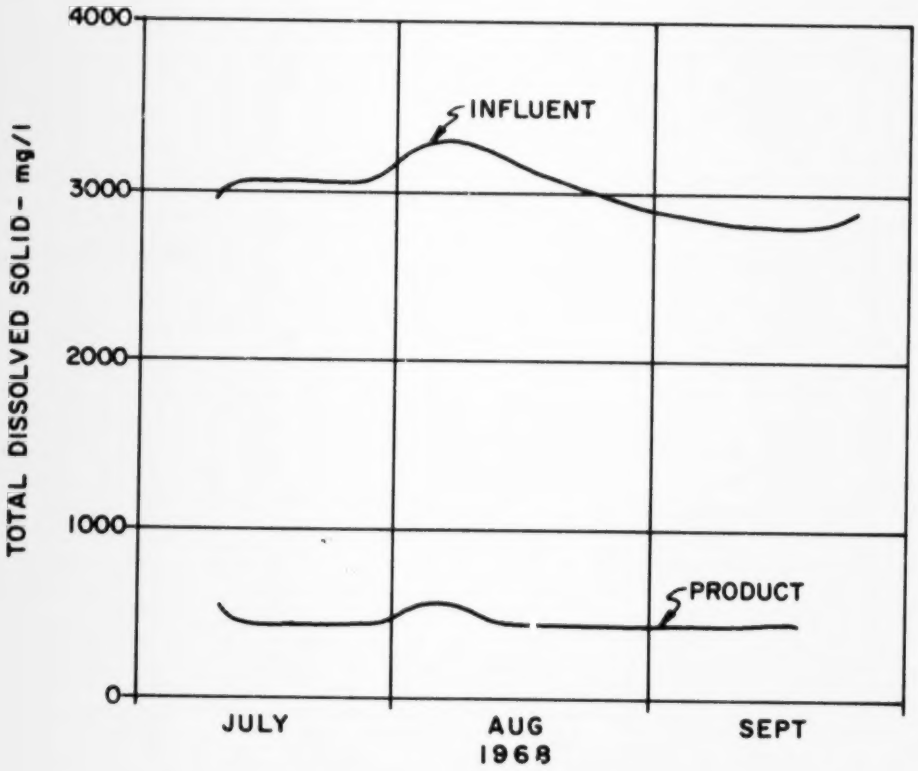

FIGURE 11 - REVERSE OSMOSIS DATA - STACK II
TOTAL DISSOLVED SOLIDS vs TIME

unit's salt rejection remained constant at 85 percent which produced a product containing a TDS of between 400 and 600 mg/l. The only variation in product TDS occurred as the influent TDS concentration varied; thus, the minor increase in product TDS could be increased salt transport through the membrane. A typical influent product and brine stream analysis for this stack is presented in Table 4. Due to the lower salt rejection capability of the membranes in this stack, its nitrate and boron removals were essentially zero.

TABLE 4

REVERSE OSMOSIS
STACK II
MINERAL ANALYSIS

Operating Conditions

Date of Sample - August 9, 1968
Operating Pressure, psig - - - - - - - - - - - - - - - 375
pH of feed water - - - - - - - - - - - - - - - - - - - 5.3

Flow Rates GPM	Influent - - - - - - - - - - - - -	13
	Product - - - - - - - - - - - - -	5.8
	Brine - - - - - - - - - - - - -	7.2

CONSTITUENT	CONCENTRATION - mg/l FEED	PRODUCT	BRINE	PERCENT REJECTION
Calcium	157	3.3	331	98
Magnesium	85	1.2	161	98
Sodium	665	140	1270	82
Potassium	4.3	1.0	7.0	77
Boron	7.0	7.0	7.3	0
Sulfate	1650	6.9	3480	99
Bicarbonate	55	21	79	62
Chloride	320	196	400	39
Nitrate	22	24	20	0
Iron (total)	0.05	0.02	0.04	60
Silicon	30	17	48	77
Total Alkalinity	46	17	65	63
TDS	2930	381	5900	87
pH*	6.8	6.8	7.0	-

*pH of samples at time of analysis

Variations in Product Flux. Product flux varied widely (Figure 12). The variations occurred under constant operating conditions, apparently independently of any exterior operational changes. As mentioned previously, disassembly of this reverse osmosis stack disclosed that the brine flow paths on the desalination plates were blocked, causing the differential pressure to increase from 35 psig to more than 95 psig through the stack. This blockage reduced the effective pressure by 20 percent which directly influenced the flux.

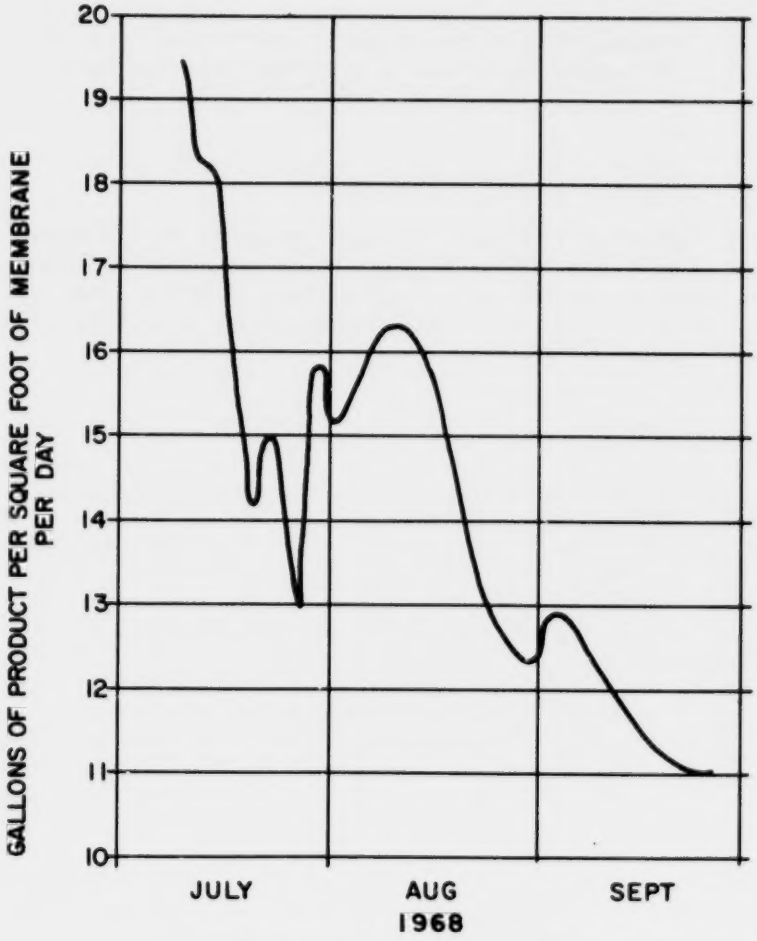

FIGURE 12 - REVERSE OSMOSIS DATA
STACK II
PRODUCT FLUX VERSUS TIME

It was also postulated that the closed brine stream reduced the effective membrane area of the unit by bridging the spiral flow path with precipitated salt. This reduced exposure of the water to the membranes and again caused a decrease in product flux.

Product Recovery. This reverse osmosis stack was designed to have a high product recovery ratio, and initially it did. On the first day of operation it recovered approximately 50 percent of the influent; however, within 14 days, this percentage decreased to approximately 36 percent. By the end of the experiment, product recovery was less than 31 percent. Such drastic changes in such a short period were assumed to be the result of the internal damage and not typical of expected results. Nevertheless, even at the highest recoveries, the amount of brine produced would equal the product and would involve brine disposal problems.

Electrodialysis

Although the electrodialysis unit (ED) was operated in the summers of 1967 and 1968, a more consistent operation was possible in 1968; this report is concerned primarily with that period. During 1968, the unit was operated on essentially the same blended water as was the reverse osmosis unit (Figure 11).

TDS Removal

The percent TDS removal and effluent TDS concentrations for the electrodialysis unit are shown in Figure 13. The variations in TDS removal from 36 percent to less than 20 percent were highly dependent on the physical condition of the membranes. In general, any sudden increase in TDS removal was due to a cleansing of the membranes. The general decline in efficiency from early August through September was attributed partially to a 10°C decline in influent water temperature and partially to a general chemical and/or biological fouling of the membranes. Substances that frequently accumulated within the stack were precipitated salts, biological slimes, and suspended solids. Any fouling of the membranes increased the electrical resistance in the stack, which lowered the TDS removal capacity of the unit. A typical mineral analysis of the three flow streams in the unit is shown in Table 5.

Nitrate was removed at an average rate 1.98 times that calculated for total dissolved solids. This factor compares favorably with the removal range of values reported by Ionics, Incorporated, which was 1.47 to 2.47 times the TDS removal (4). No significant boron removal was observed at any time.

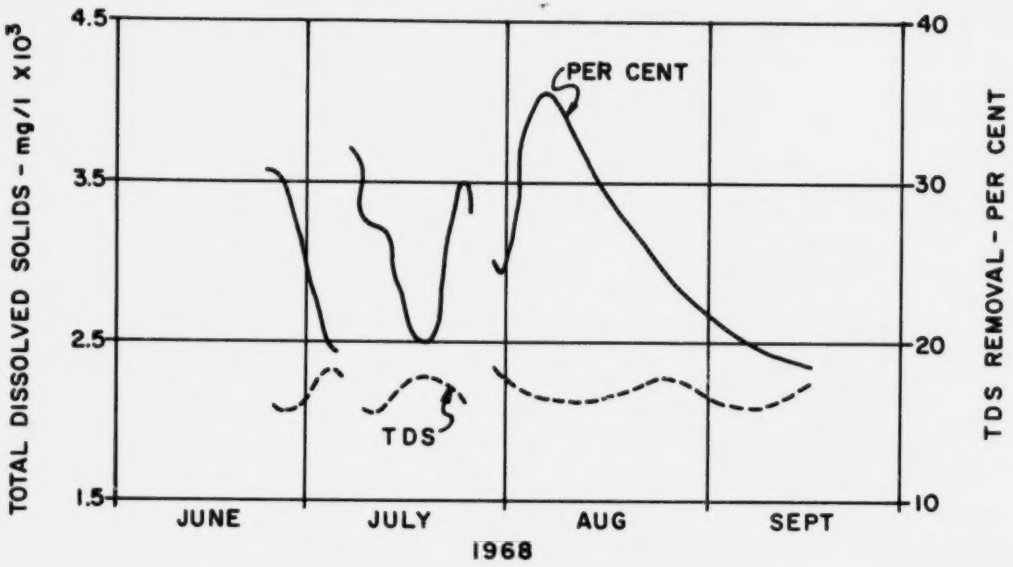

FIGURE 13 - ELECTRODIALYSIS DATA
PRODUCT TOTAL DISSOLVED SOLIDS
AND PER CENT REMOVAL OF TDS VERSUS TIME

Product Recovery Rates

The design of this unit permitted product recovery to vary only through increases or decreases in the amount of water needed to prevent saturation of salts in the recirculating brine stream. For the experiment, this requirement was kept constant at 8 gpm; thus, with a constant product flow of 25 gpm, the product recovery was approximately 75 percent. On the surface, this appears to be a better ratio than that achieved by the reverse osmosis unit; however, it should be remembered that to achieve a product of similar quality, the product stream must be passed through a series of stacks, thus ultimately yielding a larger quantity of brine.

Cost Comparison for
Reverse Osmosis and Electrodialysis

The costs of power, chemicals, and supplies for both the RO and ED units for operation on the 3000 mg/l TDS blended feed water are summarized in Table 6. The costs presented for the ED are based on a single pass through demineralizing stack and, therefore, can not be readily compared to the costs of the RO unit.

TABLE 5

ELECTRODIALYSIS DATA
MINERAL ANALYSIS

OPERATING CONDITIONS

Date of Sample - - - - - - - - - - - - - - - - - - - July 15, 1968
pH of brine stream - - - - - - - - - - - - - - - - - 5.9
Temperature of influent- - - - - - - - - - - - - - - 24
Applied E. M. F. - volts - - - - - - - - - - - - - - 276
Stack current - amperes- - - - - - - - - - - - - - - 13

Flow Rates GPM	Influent - - - - - - - - - -	33
	Product- - - - - - - - - -	25
	Brine- - - - - - - - - - -	8

CONSTITUENT	CONCENTRATION - mg/l FEED	PRODUCT	BRINE	PERCENT REJECTION
Calcium	167	105	321	37
Magnesium	68	51	138	10
Sodium	625	515	1060	18
Potassium	4.0	2.5	7.6	38
Boron	6.7	6.5	6.7	3
Sulfate	1430	1140	2580	20
Bicarbonate	336	230	147	32
Chloride	167	157	593	6
Nitrate	26	14	54	46
Iron (Total)	0.02	0.02	0.02	0
Silicon	29	30	29	0
TDS	3010	2240	5240	26
pH*	8.1	7.9	7.6	-

pH* of samples at time of analysis.

TABLE 6

COST ANALYSIS SUMMARY FOR
REVERSE OSMOSIS AND ELECTRODIALYSIS UNITS

ITEM	COST PER UNIT	QUANTITY USED PER MILLION GALLONS OF PRODUCT		COST PER MILLION GALLONS OF PRODUCT	
		RO	ED	RO	ED
Sulfuric Acid	$31.60*/Ton	2.74 Tons	1.04 Tons	$86.50	$32.86
Filter Cartridges	$0.75/Each	2.50	100	$197.50	$79.00
Electrical Power	$0.01/KWH	6700 KWH	4250 KWH	$67.00	$42.50
Cyanamer P-35	$1.00/lb	59 lbs	--	$59.00	--
TOTALS				$410.00	$154.36

*Based on tankcar lots.

The amount of materials used in these calculations was based on actual quantities used to achieve the product water produced at the Interagency Agricultural Wastewater Treatment Center. No consideration was given to capital cost, cost of operation and maintenance, or cost of brine disposal. Because of the small scale of the units and because the primary objective was determination of technical feasibility of the units, the costs for supplies and chemicals alone are high. Other published estimates have shown the cost of large-scale reverse osmosis plants to be considerably less than the prorated costs found in these experiments.

An economic evaluation study performed by Kaiser Engineers (5) has published costs for a 50 mgd plate and frame module type of reverse osmosis plant based on the following factors:

Plant	30 years
Membrane Life	1 year
Stream Factor	90 percent
Fixed Charge Rate @ 3 1/4% Interest	5.27 percent
Insurance	0.25 percent
Taxes	1.50 percent
Brine Disposal	$0.02/KGAL
Product Recovery	50 percent
Power Cost	$0.010/KWH
Influent TDS	3000 mg/1

The product water cost for such a plant was approximately 32 cents per 1000 gallons. These figures were based on present membrane technology. Costs may be reduced by 30 to 40 percent with projected improvements in membrane technology.

Cost data have been published for a 50 mgd electrodialysis plant with a demineralizing stack flow path similar to that of the smaller scale plant at the Interagency Agricultural Wastewater Treatment Center and designed under the following criteria: (6)

Plant Life	30 years
Membrane Life	3-5 years
Stream Factor	90 percent
Fixed Charge Rate @ 3 1/4%	5.27 percent
Insurance	0.25 percent
Brine Disposal	$0.020/KGAL
Power Cost	$0.007 - $0.01/KWH
Influent TDS	3638 mg/1

The product water cost for the above plant was also approximately 32 cents per 1000 gallons. Technical improvements in critical components, materials, and process design could result in a 33 percent cost reduction as compared to the present state-of-the-art.

SECTION V

ACKNOWLEDGMENTS

The desalination investigations were performed under the direction of Percy P. St. Amant, Sanitary Engineer, Environmental Protection Agency. The field work was the responsibility of Bryan R. Sword, Sanitary Engineer, Environmental Protection Agency.

The Office of Saline Water provided the desalination equipment and technical advice for the Federal Water Quality Administration's use.

The assistance given by Mr. Warren H. Bossert, formerly of the Aerojet-General Corporation, proved invaluable in maintaining and operating the reverse osmosis unit.

The assistance given by the Field Operations Office of Ionics, Inc. in providing guidelines for operation of the electrodialysis unit is gratefully acknowledged.

A major contribution to the studies was given by the efforts of the United States Bureau of Reclamation technicians, Messrs. Norman W. Cederquist, Gary E. Keller, Gary L. Rogers, and Mathew C. Rumboltz.

This report was prepared by Bryan R. Sword, Sanitary Engineer, Environmental Protection Agency.

SECTION VI

REFERENCES

1 Merten, U., Lonsdale, H. K., Riley, R. L., Vos, K. D., Reverse Osmosis for Water Desalination, Office of Saline Water, Research and Development, Progress Report No. 208, September 1966.

2 Standard Methods for the Examination of Water and Wastewater, American Public Health Association, Inc., New York, 12th Edition (1965).

3 Correspondence with Aerojet-General Corporation, February 5, 1968.

4 Katz, William E., Nitrate Removal by Electrodialysis - A Brief Review, Ionics, Incorporated, October 25, 1966.

5 Harris, F. L., Engineering and Economic Evaluation Study of Reverse Osmosis, Office of Saline Water, Second Symposium on Reverse Osmosis, April 1969.

6 Christodoulou, G. R., Olsson, G. R., Monnik, H. J., Parametric Economic and Engineering Evaluation Study of the Electrodialysis Process for Water Desalination, Office of Saline Water, Research and Development Progress Report No. 488.

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SECTION VII

PUBLICATIONS

SAN JOAQUIN PROJECT, FIREBAUGH CALIFORNIA

1968

"Is Treatment of Agricultural Waste Water Possible?"
Louis A. Beck and Percy P. St. Amant, Jr. Presented at Fourth International Water Quality Symposium, San Francisco, California, August 14, 1968; published in the proceedings of the meeting.

1969

"Biological Denitrification of Wastewaters by Addition of Organic Materials"
Perry L. McCarty, Louis A. Beck, and Percy P. St. Amant, Jr. Presented at the 24th Annual Purdue Industrial Waste Conference, Purdue University, Lafayette, Indiana. May 6, 1969.

"Comparison of Nitrate Removal Methods"
Louis A. Beck, Percy P. St. Amant, Jr., and Thomas A. Tamblyn. Presented at Water Pollution Control Federation Meeting, Dallas, Texas. October 9, 1969..

"Effect of Surface/Volume Relationship, CO_2 Addition, Aeration, and Mixing on Nitrate Utilization by Scenedesmus Cultures in Subsurface Agricultural Waste Waters".
Randall L. Brown and James F. Arthur. Proceedings of the Eutrophication-Biostimulation Assessment Workshop, Berkeley, California. June 19-21, 1969.

"Nitrate Removal Studies at the Interagency Agricultural Waste Water Treatment Center, Firebaugh, California"
Percy P. St. Amant, Jr., and Louis A. Beck. Presented at 1969 Conference, California Water Pollution Control Association, Anaheim, California, and published in the proceedings of the meeting. May 9, 1969.

"Research on Methods of Removing Excess Plant Nutrients from Water"
Percy P. St. Amant, Jr., and Louis A. Beck. Presented at 158th National Meeting and Chemical Exposition, American Chemical Society, New York, New York. September 8, 1969.

"The Anaerobic Filter for the Denitrification of Agricultural Subsurface Drainage"
T. A. Tamblyn and B. R. Sword. Presented at the 24th Purdue Industrial Waste Conference, Lafayette, Indiana. May 5-8, 1969.

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SAN JOAQUIN PROJECT, FIREBAUGH, CALIFORNIA (Continued)

1969

"Nutrients in Agricultural Tile Drainage"
W. H. Pierce, L. A. Beck and L. R. Glandon. Presented at the 1969 Winter Meeting of the American Society of Agricultural Engineers, Chicago, Illinois. December 9-12, 1969.

"Treatment of High Nitrate Waters"
Percy P. St. Amant, Jr., and Perry L. McCarty. Presented at Annual Conference, American Water Works Association, San Diego California. May 21, 1969. American Water Works Association Journal. Vol. 61. No. 12. December 1969. pp. 659-662.

The following papers were presented at the national Fall Meeting of the American Geophysical Union, Hydrology Section, San Francisco, California. December 15-18, 1969. They are published in Collected Papers Regarding Nitrates in Agricultural Waste Water. USDI, FWQA, #13030 ELY December 1969.

"The Effects of Nitrogen Removal on the Algal Growth Potential of San Joaquin Valley Agricultural Tile Drainage Effluents"
Randall L. Brown, Richard C. Bain, Jr. and Milton G. Tunzi.

"Harvesting of Algae Grown in Agricultural Wastewaters"
Bruce A. Butterfield and James R. Jones.

"Monitoring Nutrients and Pesticides in Subsurface Agricultural Drainage"
Lawrence R. Glandon, Jr., and Louis A. Beck

"Combined Nutrient Removal and Transport System for Tile Drainage from the San Joaquin Valley"
Joel Goldman, James F. Arthur, William J. Oswald, and Louis A. Beck.

"Desalination of Irrigation Return Waters"
Bryan R. Sword.

"Bacterial Denitrification of Agricultural Tile Drainage"
Thomas A. Tamblyn, Perry L. McCarty and Percy P. St. Amant.

"Algal Nutrient Responses in Agricultural Wastewater"
James F. Arthur, Randall L. Brown, Bruce A. Butterfield, Joel C. Goldman